High Capacity Heat Pipe Performance Demonstration

Final Report

Contract NAS9-16582

19 December 1983

Submitted to:

National Aeronautics and Space Administration
Johnson Space Center

By:

Vought Corporation
Dallas, Texas

LTV Vought

FINAL REPORT

HIGH CAPACITY HEAT PIPE PERFORMANCE DEMONSTRATION

CONTRACT NAS9-16582

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SUBMITTED TO:

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHNSON SPACE CENTER
HOUSTON, TEXAS

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1.0 SUMMARY

This report describes efforts to develop a high capacity heat pipe which will operate in one-g and in zero-g. The period of performance was May 1982 through February 1983. This effort is a continuation of a program described in a presentation to NASA-JSC on 3 November 1981. The primary objective of the current work was to obtain an artery configuration which is self-priming in one-g.

Two artery modifications were evolved as candidates to achieve one-g priming and will provide the very high performance: the four artery and the eight artery configurations shown in Figures 2 and 3. These were each evaluated analytically for performance and priming capability. The eight artery configuration was found to be inadequate from a performance standpoint. The four atery showed promise of working. A five-inch long priming element test article was fabricated using the four artery design. Plexiglas viewing windows were made on each end of the heat pipe to permit viewing of the priming activity.

The five-inch primary element would not successfully prime in one-g. Difficulties on priming in one-g raised questions about zero-g priming. Therefore a small test element heat pipe for verifying that the proposed configuration will self-prime in zero-g was fabricated and delivered to NASA-JSC. This test article was carried on a KC-135 aircraft which was flown in parabolic trajectories to similate zero-g for short durations of about 30 seconds. The heat pipe did not prime in the approximately 10 seconds of free-float during the simulations. The problem with the zero-g priming is suspected to be either non-condensible gas generation or insufficient time to condense the vapor in the artery.

2.0 BACKGROUND AND INTRODUCTION

In 1980 Vought began investigation of high capacity heat pipes for use with NASA's Constructable Radiator System. The system used long heat pipes (50-60 feet) which are plugged into contact heat exchangers which interface with a flow loop that collects heat from around the spacecraft. The heat pipe needs to have the capability for high performance (in the range of 700,000 - 1,500,000 watt-inches). The most effective contact heat exchanger design requires the evaporator section of the heat pipe which plugs into the contact heat exchanger to be round. The round heat pipe with the liquid artery in the middle has the distinct advantage that heat can be added around the entire periphery of the heat pipe while the liquid in the artery remains subcooled.

Vought designed and built such a heat pipe, using an internal artery, in 1980 for exploratory development purposes. The Vought design used a circumferentially grooved heat pipe with an internal artery in a "cat's eye" configuration.

It is also desirable for the heat pipe to function properly in a one-g environment. This would permit the heat pipe to be ground tested prior to flight. Vought tested the heat pipe with the "cat's eye" artery, and found that it would not function properly in one-g due to failure to self-prime. At that time two new artery configurations were postulated which, it was thought, would self-prime. One of these was a "modified cat's eye" configuration and the other was a radial spoke configuration.

In May 1982 NASA-JSC funded Vought to evaluate these two new internal artery configurations. The low level funding was intended to investigate this design as a potential alternative to the baselined monogroove heat pipe currently under development by the Grumman Corporation. This report describes the results of the effort to develop the alternative heat pipe.

3.0 TECHNICAL DISCUSSION

3.1 Artery Design

Under prior internal funding Vought built a 4-ft. long, high capacity heat pipe using circumferential grooves as shown in Appendix A and an internal artery configuration as shown in Figure 1. The working fluid was ammonia. Performance tests on this heat pipe indicated that the artery was not primed. To verify this a 5-inch long element of the heat pipe was made and equipped with plexiglas end caps. This test article was filled with colored water as the working fluid. This test demonstrated conclusively that the "cat's eye" artery would not self-prime in one-g. Based on observation of the water action in the artery it was concluded that a "modified cat's-eye", shown in Figure 2, would probably prime. The key feature of the "modified cat's eye" artery was that liquid would not have to be pumped above the artery inlet when in the orientation shown in Figure 2.

A second artery design was evolved as shown in Figure 3. This configuration has numerous artery flow paths which are narrow enough that capillary forces are strong enough to lift liquid up the entire height of the artery.

The fabrication approach for both candidate artery configurations was to purchase simple extrusion shapes which could be installed in the heat pipe to form the desired configuration. The extrusion configurations are shown in Figures 3 and A-3. These extrusion shapes were ordered early in the program.

3.2 Performance

Performance analyses were made for both of the artery configurations for ammonia and R11 working fluids. Results of these analyses are given in Table I. Working Fluid properties are given in Table II. As can be seen, the radial spoke artery configuration does not approach the desired performance level of 700,000 - 1,500,000 watt-in. For this reason this artery configuration was not pursued, though the extrusion was successfully made by the vendor. (The extrusion was made as one-eighth of the artery as shown in Figure 3).

On the other hand, the projected performance of the modified cat's eye is predicted to meet the need of the Space Constructable Radiator with 1,500,000 watt-inches. This is with a one-inch external diameter configuration shown in Figure 2. The space constructable radiator needs approximately 720,000 watt-inches for a 2 kW, 60 foot long heat pipe. Heat can theoretically be added to the entire circumference of the cat's eye heat pipe. The performance predictions in Table I were based upon a 13-1/2 inch evaporator, 13-1/2 inch condensor and a 21 inch adiabatic section for the 4 foot long heat pipe. For the 50 foot long heat pipe, a four foot evaporator and 46 foot condensor were assumed. The temperature drop from heat transport fluid in an external contact heat exchanger to the heat pipe fluid in the 4-foot evaporator is estimated to be 5°F for a 1 kW heat load or 10°F for a 2 kW heat load. The four feet evaporator could be configured in four 1-foot lengths or two 2-foot lengths if desired. The estimated dry weight of the heat pipe is .39 LB/FT for a 0.080 inch wall or .32 LB/FT for a .060 inch wall. Ammonia fluid will add approximately 0.04 LB/FT.

NOTES:
1. FILLET RADII .03
2. MATERIAL 6063-T6
3. TOLERANCES PER FED-STD-245 EXCEPT AS SPECIFIED
4. THIS DIMENSION TO BE CONFIRMED PRIOR TO MANUFACTURE OF PARTS.

FULL SIZE

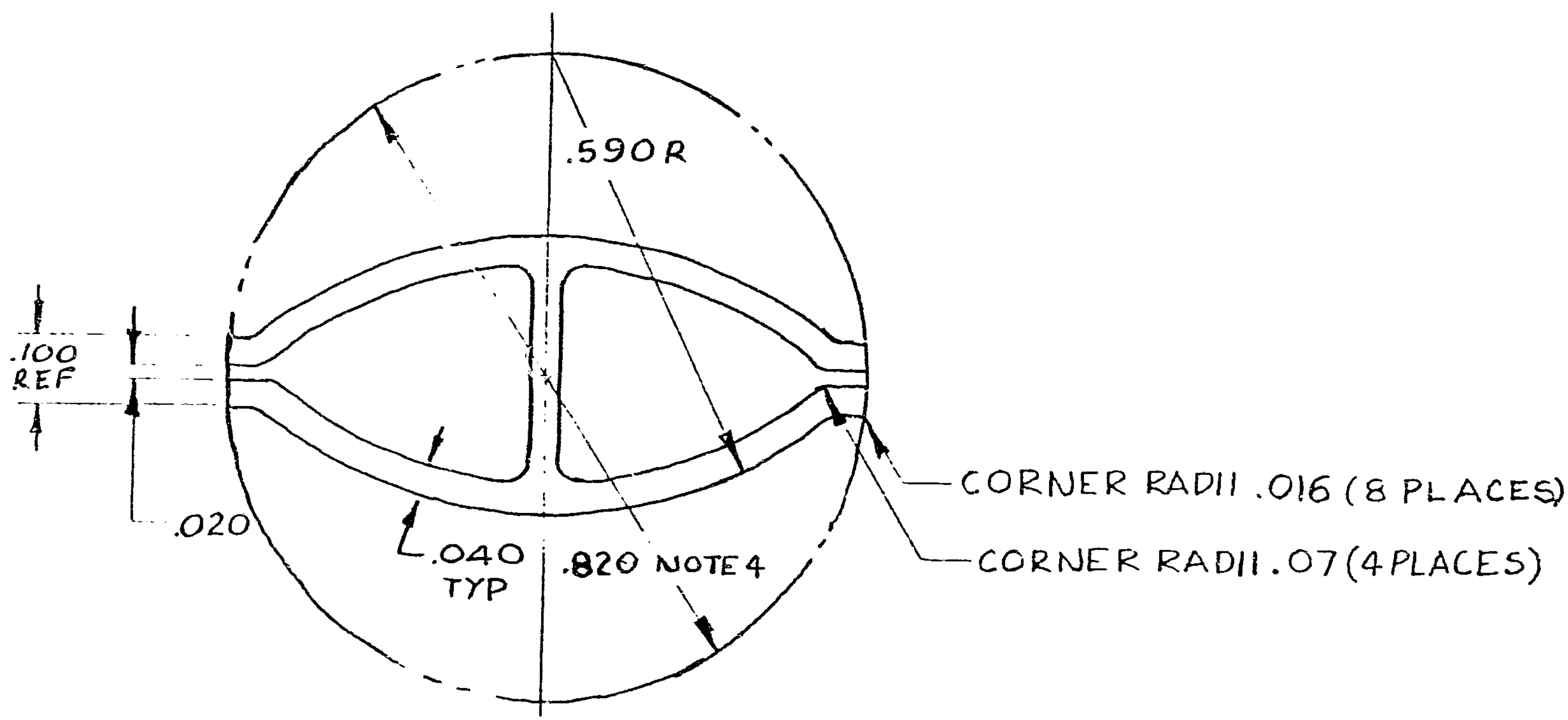
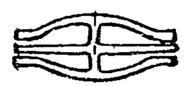


FIGURE 1 CAT'S EYE ARTERY

CONTR NO.			VOUGHT CORPORATION		Post Office Box 225907 Dallas, Texas 75265	
PREP	K. DOUGAN	2/5/81	EXTRUSION HEAT PIPE			
CHKD	D. D. STALMACH	2/10/81				
DESIGN GROUP NAME			SIZE	FSCM NO. 80378	DWG NO. 221-60121	REV



FULL SIZE

NOTES:

1. FILLET RADII 0.03
2. MATERIAL 6063-T6
3. TOLERANCE PER FED-STD-245 EXCEPT AS SPECIFIED

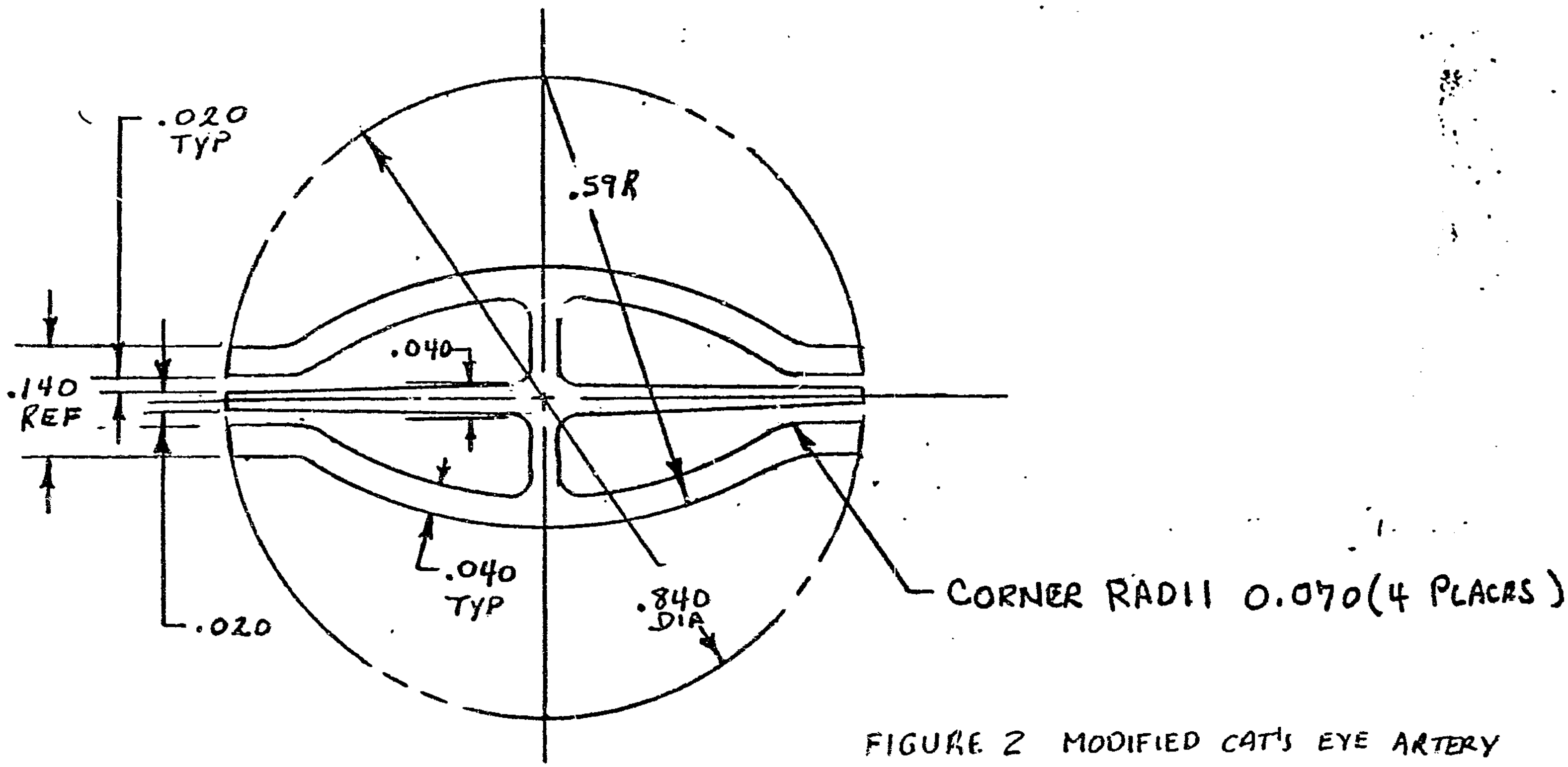


FIGURE 2 MODIFIED CAT'S EYE ARTERY

CONTR NO.			VOUGHT CORPORATION		Post Office Box 225907 Dallas, Texas 75265
PREPARED	J. OREN	6/21/82	EXTRUSION HEAT PIPE FOUR ARTERY		
CHECKED	R. NELSON	6-22-82			
DESIGN GROUP NAME			SIZE	FSCM NO. 80378	DWG NO. 221-60129 REV
			SCALE 4X		SHEET 1 OF 1

NOTES:
1. MATERIAL 6063-
2. TOLERANCES PER FED-STD-245 EXCEPT AS SPECIFIED

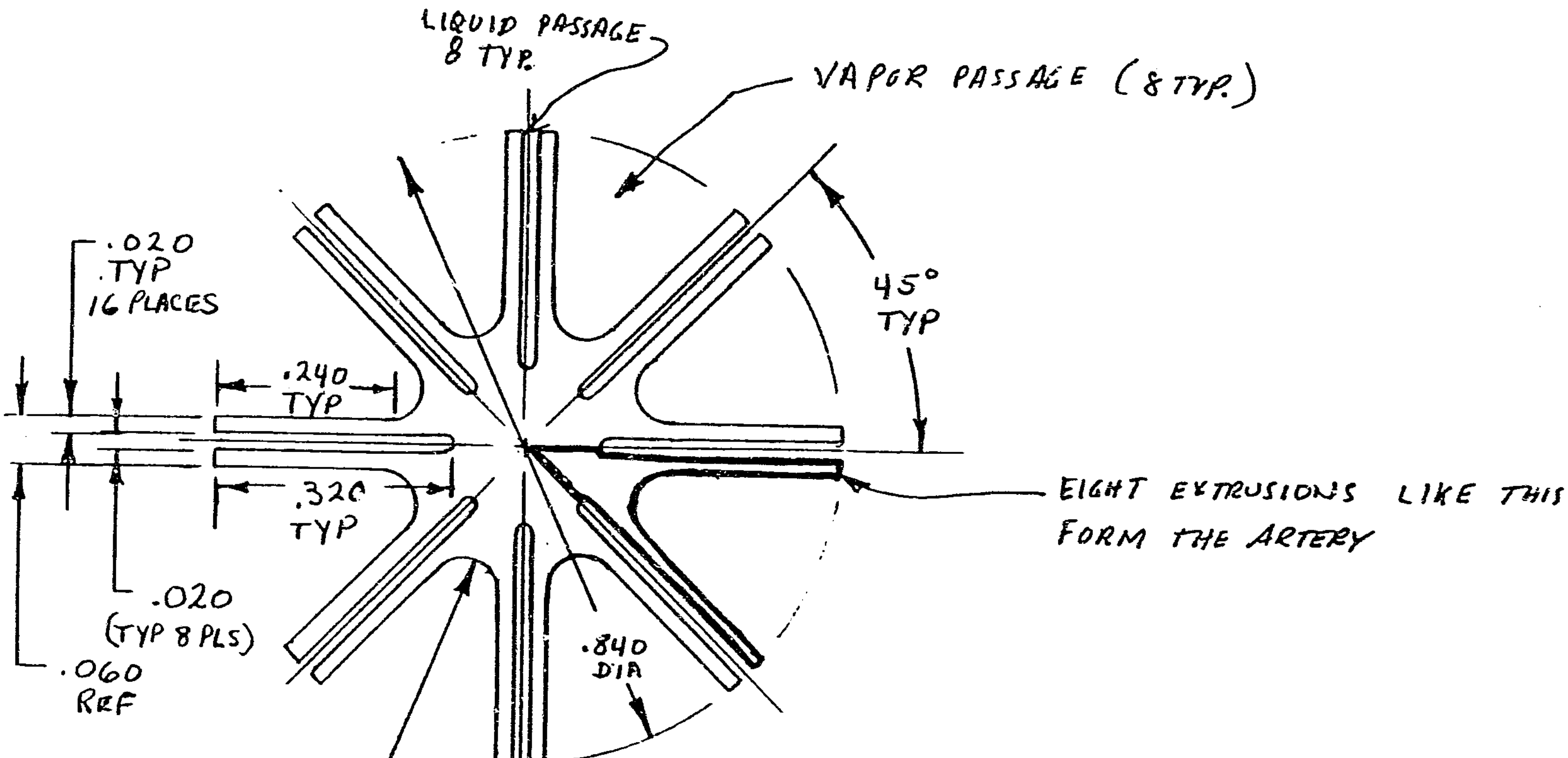


FIGURE 3 EIGHT LIQUID FLOW PATH ARTERY

CONTR NO.		
PREPARED	J. OREN	6/21/82
CHECKED	R. NELSON	6-22-80
DESIGN GROUP NAME		

VOUGHT CORPORATION Post Office Box 225907 Dallas, Texas 75265

EXTRUSION HEAT PIPE EIGHT ARTERY

SIZE	FSCM NO.	DWG NO.	REV
	80378	221-60130	
SCALE 4X		SHEET 1 OF 1	

TABLE I PREDICTED PERFORMANCE

$(QL)_{MAX}$ IN WATT-INCHES

WORKING FLUID	ARTERY CONFIGURATION	GRAVITY	ZERO-G		ONE-G	
		LENGTH, FT	4	50	4	50
Ammonia	8-Artaery		102,000	105,000	80,000	81,000
Ammonia	Modified cat's eye (4 liquid Arteries)		224,000	1,500,000	174,000	1,166,000
R11	Modified cat's eye (4 liquid Arteries)		35,000	-	16,000	-

TABLE II WORKING FLUID PROPERTIES

R11 Properties @ 70°F

	Liquid	Vapor
Density, (LB_m/ft^3)	92.35	0.406
Viscosity, $(LB_m/ft\text{-}HR)$	1.09	0.0266
Surface Tension, (LB_f/ft)	13×10^{-4}	
Latent Heat, (BTU/LB_m)	77	
Ratio of Specific Heat, (Dimensionless)		1.12
Molecular wt	137.38	

Ammonia Properties at 80°F

	Liquid	Vapor
Density, (LB_m/ft^3)	37.5	0.512
Viscosity, $(LB_m/ft\text{-}HR)$	0.516	0.0267
Surface Tension, (LB_f/ft)	0.00135	
Latent Heat, (BTU/LB_m)	500	
Ratio of Specific Heat, (Dimensionless)		1.33
Molecular wt	17	

3.3 Testing

3.3.1 Test Approach

The original plan for this program was to modify the 4-foot long heat pipe with the new artery, and with transparent ends for liquid action visualization inside the heat pipe. Designing the transparent ends for the heat pipe proved to be a difficult task because of the limited choice of transparent materials that are compatible with ammonia. For this reason the plan was modified as follows: the self-priming characteristics of the modified cat's eye artery would be verified with the 5-inch heat pipe using water and R11 as the working fluids, and results would be extrapolated to ammonia. The modified cat's eye artery would then be installed in the 4 foot long heat pipe for performance testing.

The 5-inch heat pipe was fabricated, cleaned, and vacuum filled with R11. For simplicity in this visualization test, only half of the artery was installed in the heat pipe. The artery did not prime spontaneously, and attempts to prime it by orientation changes, such as rolling the pipe about the long axis, were not successful. The R11 liquid settled in the heat pipe as depicted in Figure 4.

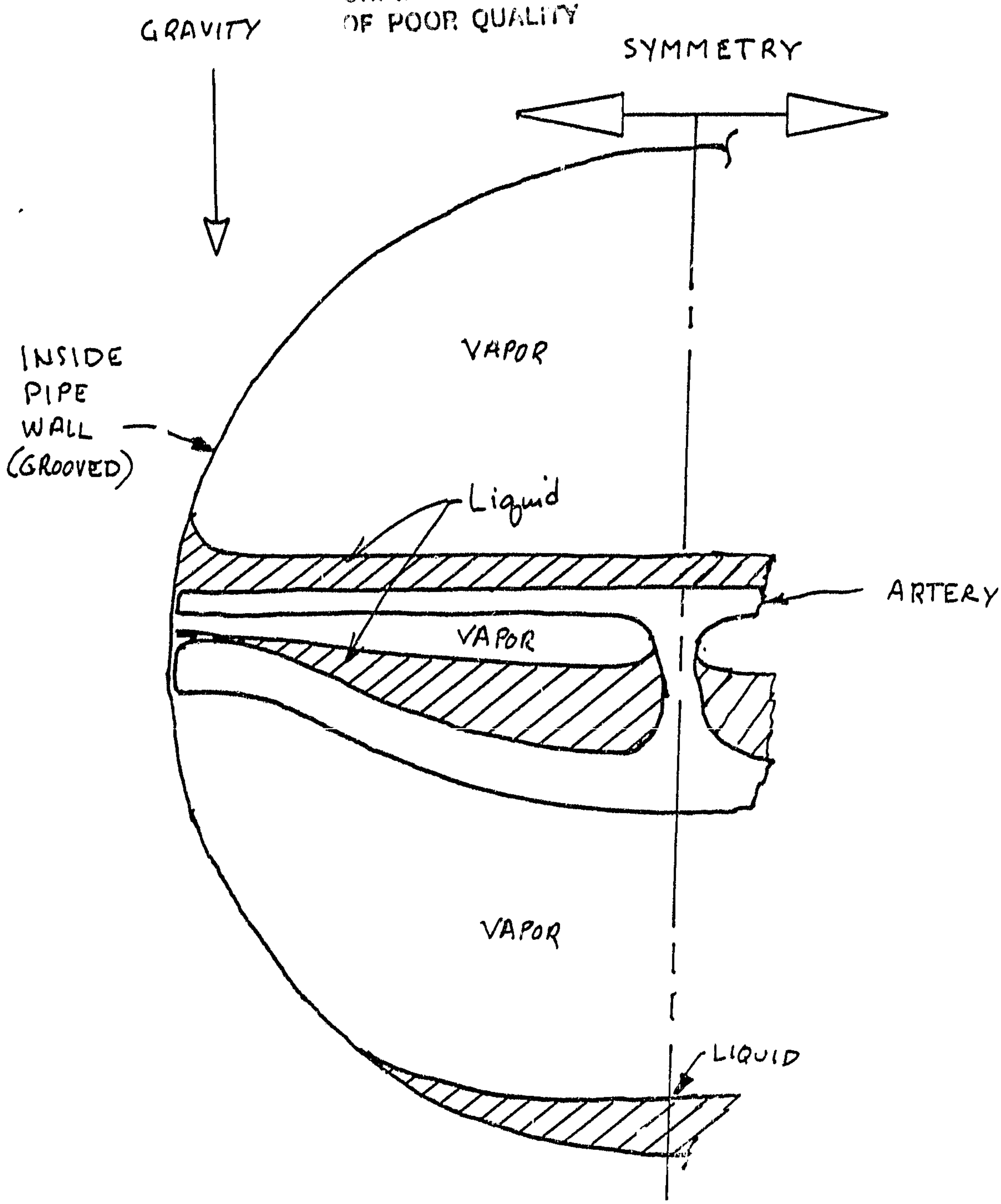
The equilibrium position shown in Figure 4 (b) suggests that the artery contains non-condensible gas. Thus, the heat pipe was disassembled, subjected to more rigorous cleaning and handling, and reassembled. During filling the pipe was subjected to a longer period of drying. Self-priming results after filling were the same as were previously experienced. R11 was then removed from the heat pipe and it was charged with water. Self-priming results were still the same. One end of the heat pipe was then heated to attempt Clausius-Clapeyron priming, but this too was unsuccessful.

It was next decided to change the transparent flange material from Plexiglas to LEXAN to allow the heat pipe to be heated as it was vacuum dryed. (Plexiglas has a temperature limit of 120°F as compared to 275°F for LEXAN). It was also decided to move the fill port from one end of the pipe to the center to allow better gas removal during bakeout. The heat pipe was thus put into the configuration described in Appendix A. It was fabricated, cleaned, and filled (after a 200°F vacuum bakeout) as described in Appendix B.

After these changes were made, the priming performance of the "modified cat's eye" artery was unchanged.

3.3.2 Discussion of Test Results

There were two primary artery orientations. In the "horizontal" orientation shown in Figure 4(a), an explanation for the failure to prime is postulated as follows: The heat pipe grooves have more then ample pumping power to fill the artery, being 1.9 inches pumping height for R11 and 5.3 inches for water (Figure 5). The meniscus across the tube wall grooves would not be flat at a height of 1/2-inch (the approximate artery height), and would appear something like the drawing section in Figure 6. Lack of continuous liquid contact with the artery wall could cause failure to prime the artery. This would not occur in a zero-g environment since liquid would wet the entire inner wall of the pipe.



SCALE : 1' ≈ 7"

FIGURE 4 (a) LIQUID POSITION WITH ARTERY HORIZONTAL

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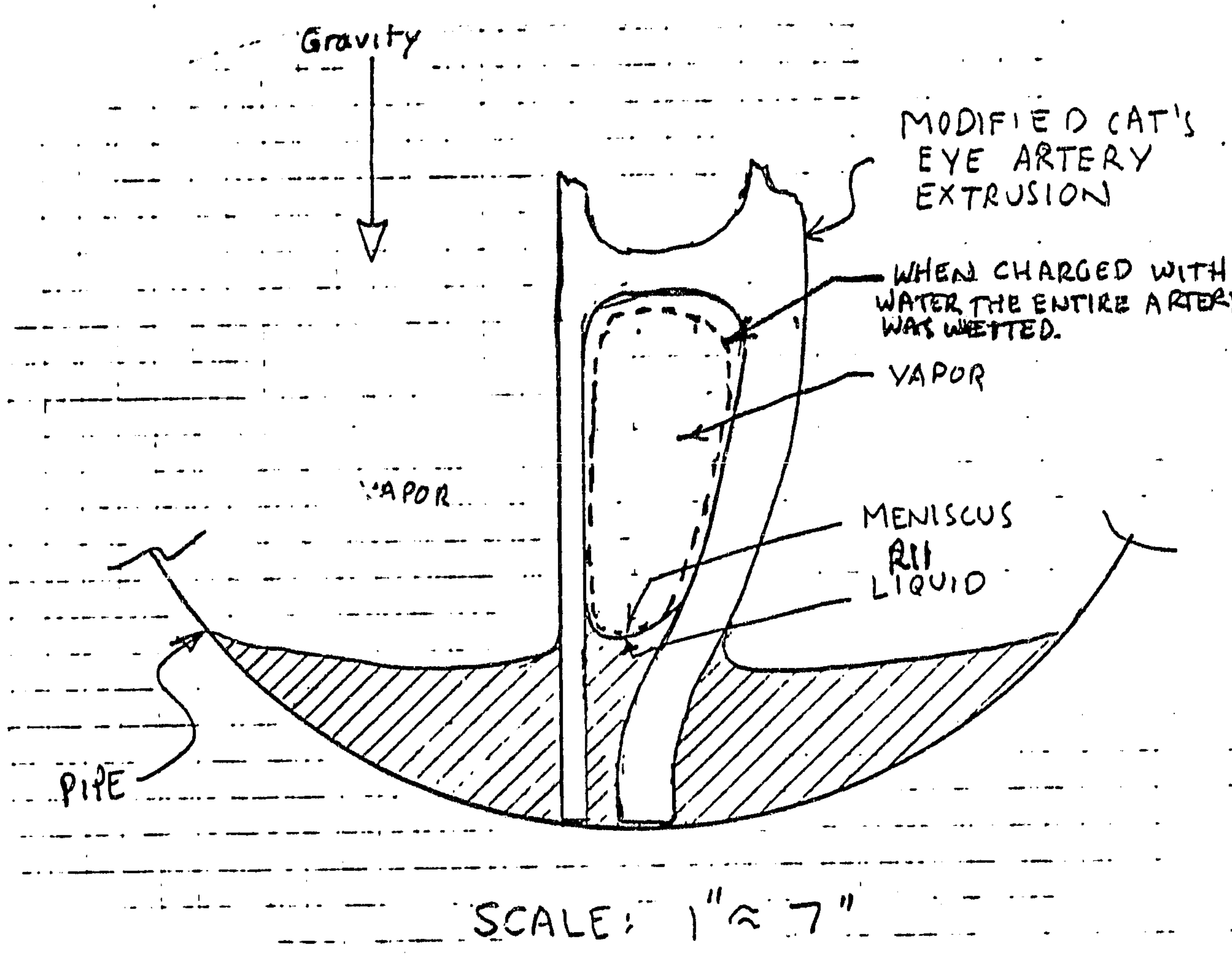

FIGURE 4 (b) LIQUID POSITION WITH ARTERY VERTICAL

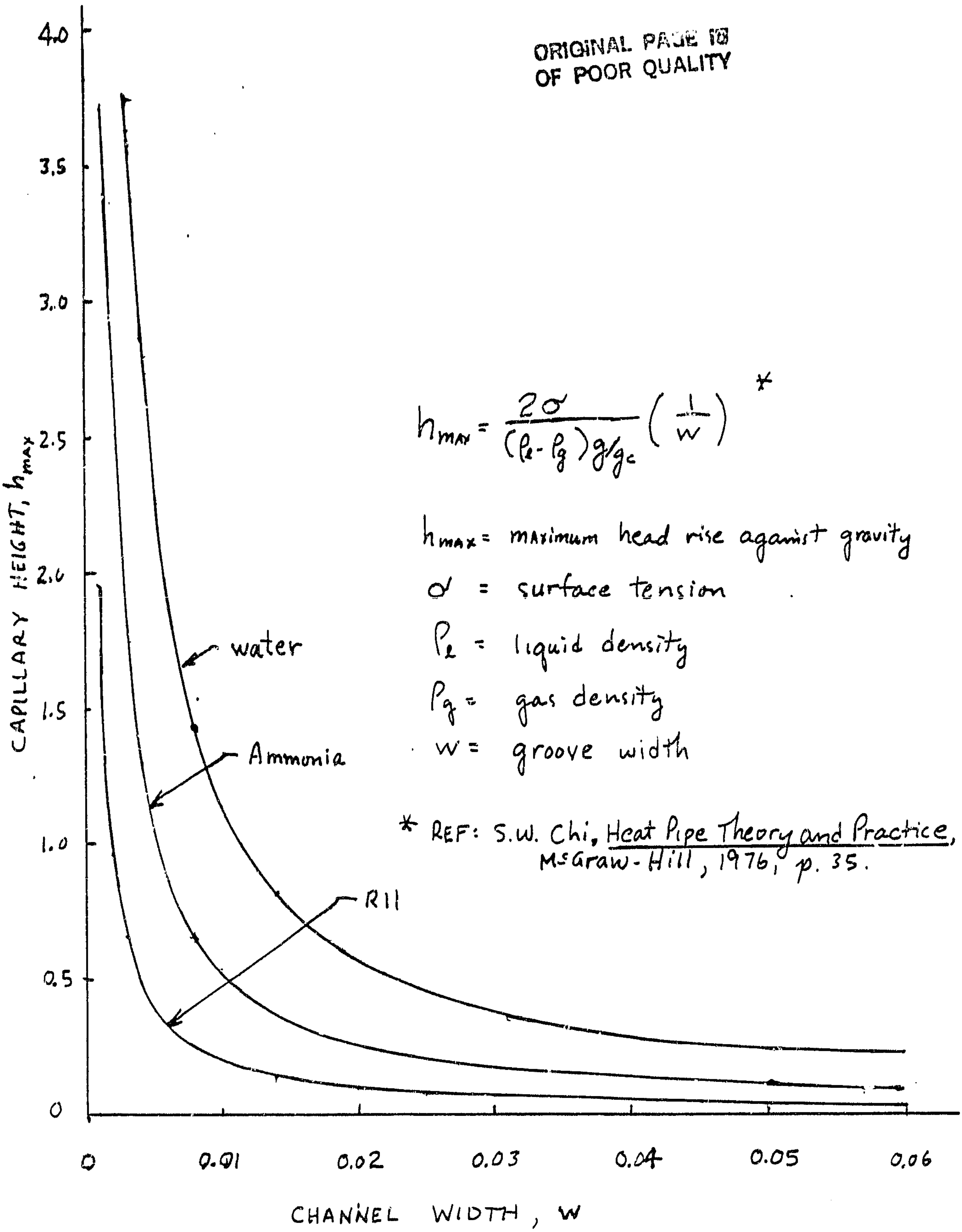

FIGURE 5 CAPILLARY RISE AS A FUNCTION OF GROOVE WIDTH

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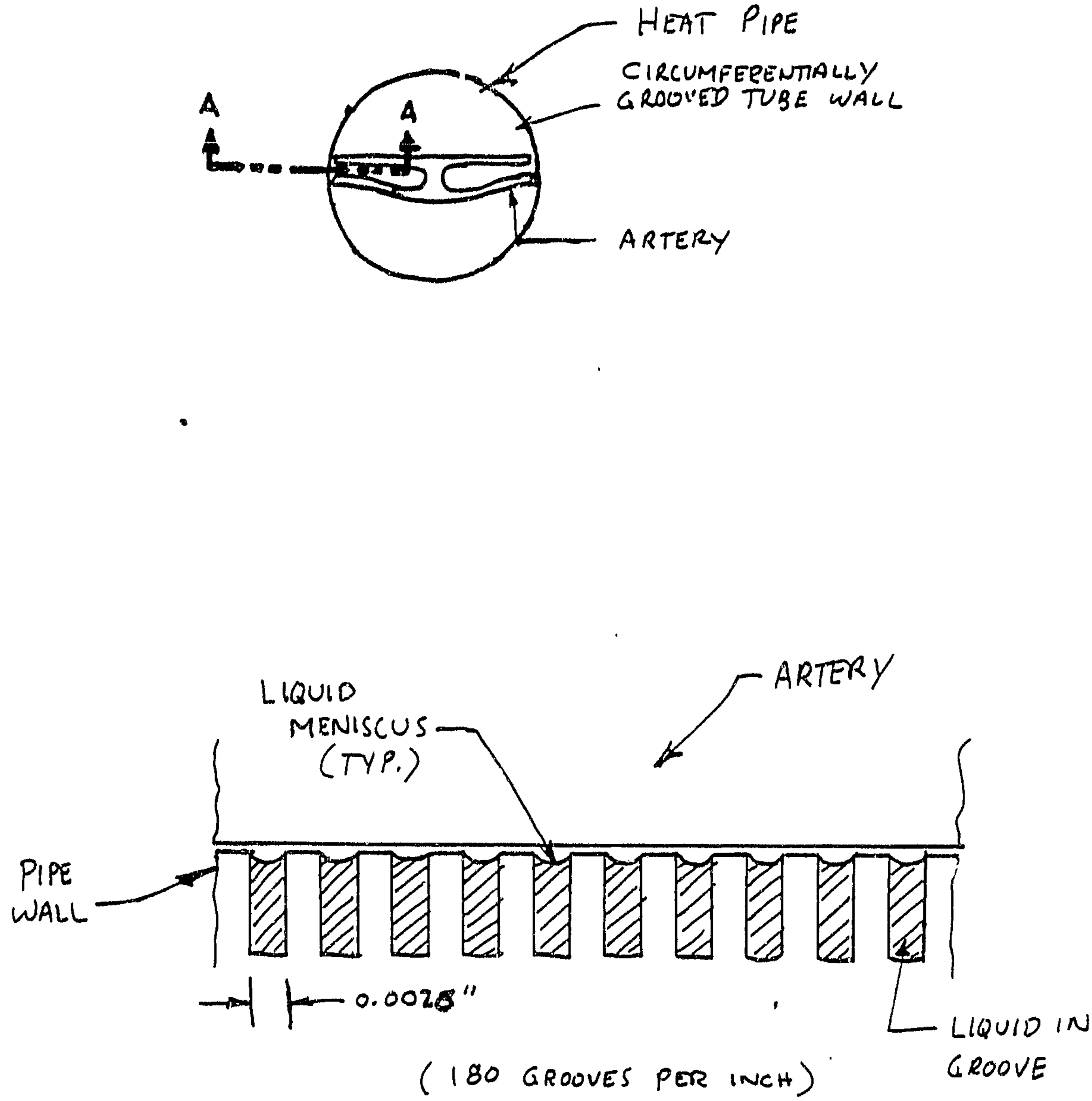

SECTION A-A

FIGURE 6 CROSS-SECTION ACROSS ARTERY INLET SHOWING LIQUID MENISCUS IN TUBE WALL GROOVES

The situation with the vertical orientation shown in Figure 4(b) is more disconcerting. The fluid in the artery will not rise to the top of the artery due to inadequate pumping power. However, the smaller meniscus radii in the artery should cause it to rise 0.019 in. above the liquid in the vapor passages for R11 and 0.114 in. for water. This did not occur. In the case of R11 the liquid rise height is small, and the average liquid level is hard to establish because of the meniscus curvature. For water the liquid rise height is larger, and so the water in the artery was expected to be noticeably higher than in the vapor spaces. This did not happen, leading to speculation that the artery contained non-condensible gas. Numerous attempts were made to reduce the amount of non-condensible products in the heat pipe, as was discussed earlier. It was not possible to heat the pipe to as high a temperature as might be desirable during the evacuation process because of the temperature limit on the plexiglas or Lexan end caps; nevertheless, measures taken were more extreme than is the usual practice in heat pipe assembly. It appears the explanation for the failure of the liquid to rise as high as would be predicted is due to non-condensible gas generation or the complex relationship within the artery. The vapor liquid interface is not in thermodynamic equilibrium due to capillary and gravitational effects. Considering capillary action alone, (in zero-g) the vapor would condense into an advancing vapor-liquid interface because the liquid pressure would always be lower than the vapor pressure. Since the liquid is much more dense than the vapor, and temperature in the heat pipe is uniform, the vapor would soon become superheated due to falling pressure. This should actually cause the vapor-liquid interface to move more rapidly into the artery vapor space. Since the liquid vapor interface has a smaller radius of curvature than the liquid-vapor interface outside of the artery in the heat pipe vapor passage, the equilibrium condition would be with the artery completely filled with liquid. Gravitation forces obviously prevent this from occurring; however, it is not clear why the liquid-vapor interface in the artery fails to rise higher in the artery than in the vapor passage. Since the interface fails to rise as would be predicted in one-g, there is a question if it will advance as predicted in zero-g.

For the above reason it was deemed prudent to check the priming action in zero-g. The 5-inch heat pipe was prepared as described in Appendix B, proof-tested to 80 psi and delivered to NASA-JSC.

The modified cat's eye heat pipe was taken on zero-g simulation flights in a KC-135 by NASA in April, 1983, to evaluate its zero-g priming. The test consisted of a visual examination of the priming for the free floating portion of the flight (about 10 to 15 seconds). About 20 of these zero-g profiles were flown. The heat pipe did not prime during any of the testing. The liquid wetted all metallic surfaces inside the heat pipe and left a vapor or gas void in all passages including the artery. As a result of this, the suspected problem is non-condensible gas generation as a result of the corrosive action of the water on the aluminum, and/or insufficient time to condense the vapor in the arteries.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The modified cat's eye artery, 1-inch nominal diameter, high capacity heat pipe could not be shown to prime in either one-g or zero-g fields. However, it is felt that for the zero-g test, and possibly for the one-g test as well, the test was inconclusive due to non-condensible gas generation resulting from chemical action between the aluminum and water working fluid.

In addition, for the zero-g test the 10 seconds free floating time may be insufficient to condense the vapor in the artery. Nevertheless, the significant promise of the round heat pipe configuration with a central artery merits continued study. The following are recommended:

1) Refill the 5-inch priming element test unit with a fluid compatible with the materials (aluminum and Lexan) and re-test on a future zero-g flight. Prior to conducting this test an estimate of the priming time should be made.

2) Investigate heat pipe/artery configuration modifications which will result in one-g priming. Demonstrate these with element tests.

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APPENDIX A

DELIVERED HEAT PIPE DESCRIPTION

The delivered heat pipe is made of a 1" Diameter aluminum tube. It is 5-1/8 inches long, and has transparent flanges on each end as shown in Figure A-1. A list of the material used in the heat pipe is also given on Figure A-1. The inside wall of the aluminum tube has circumferential grooves as shown in Figure A-2. The artery extrusion is shown in Figure A-3. Only one of these arteries is included in the delivered heat pipe. The proposed flight design has two of these arteries installed back-to-back.

LIST OF MAT'L

① 6061-T6 AL TUBE; 1 ea
② 6063-O ARTERY; 1 ea
③ Ni CLAD LOW CARBON STEEL BOLT AND NUTS (3/16" D); 4 ea
④ 9034 LEXAN (POLYCARBONATE) FLANGE; 2 ea
⑤ 2-002 BUNA-N O-RING; 2 ea
⑥ WHITEY BALL VALVE - SS 43F4; 1 ea
⑦ AN929-4 CAP; 1 ea
⑧ AN911-2D PIPE NIPPLE, ONE END REMOVED; 1 ea

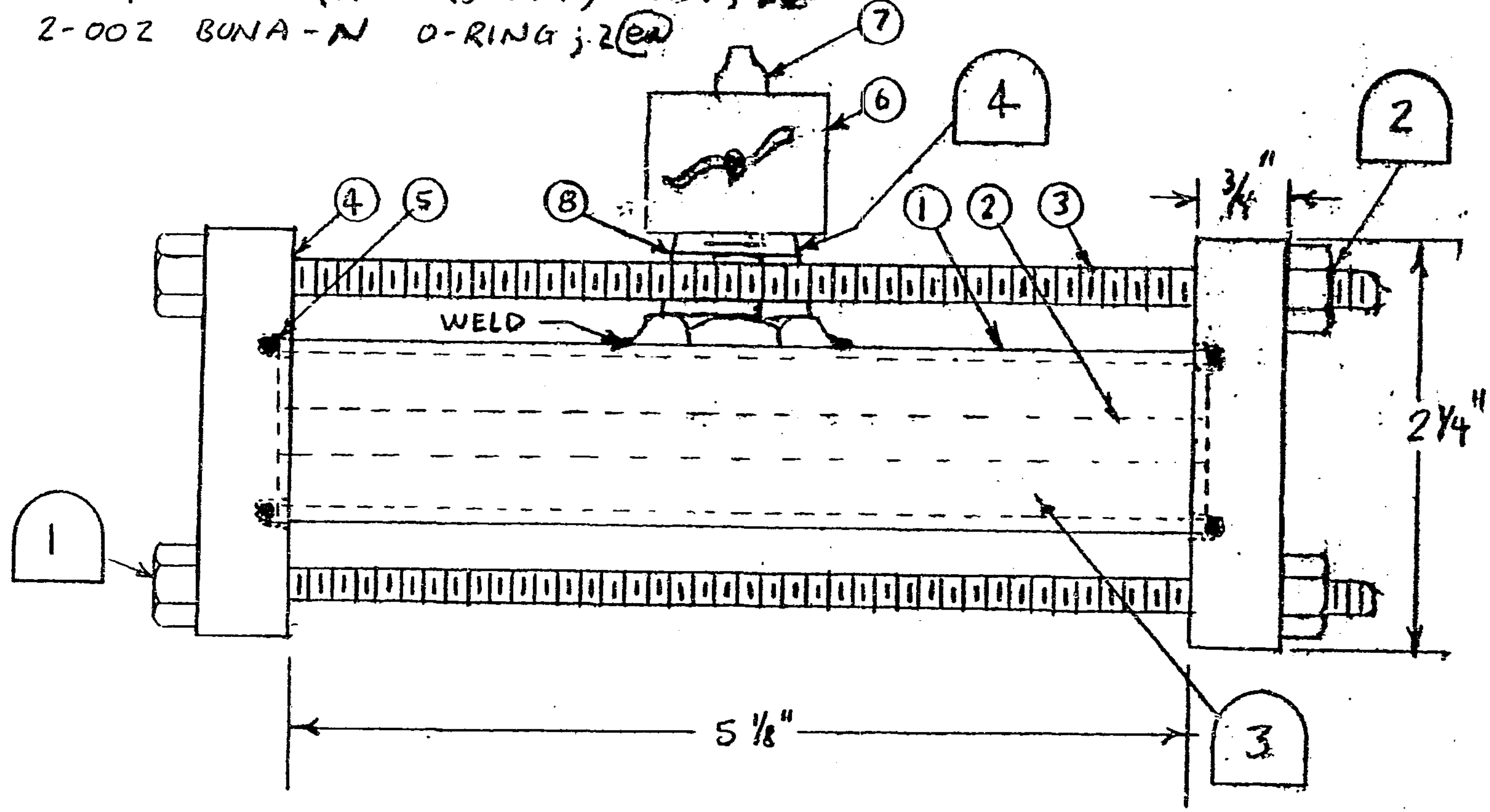

FIGURE A-1

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NOTES

[1] NUT SILVER SOLDERED TO BOLT; TYP 4 PLACES

[2] NUT INSTALLED WITH LOCTITE AND COATED WITH "FBI ANTI-SABOTAGE" PAINT; 4 PLACES

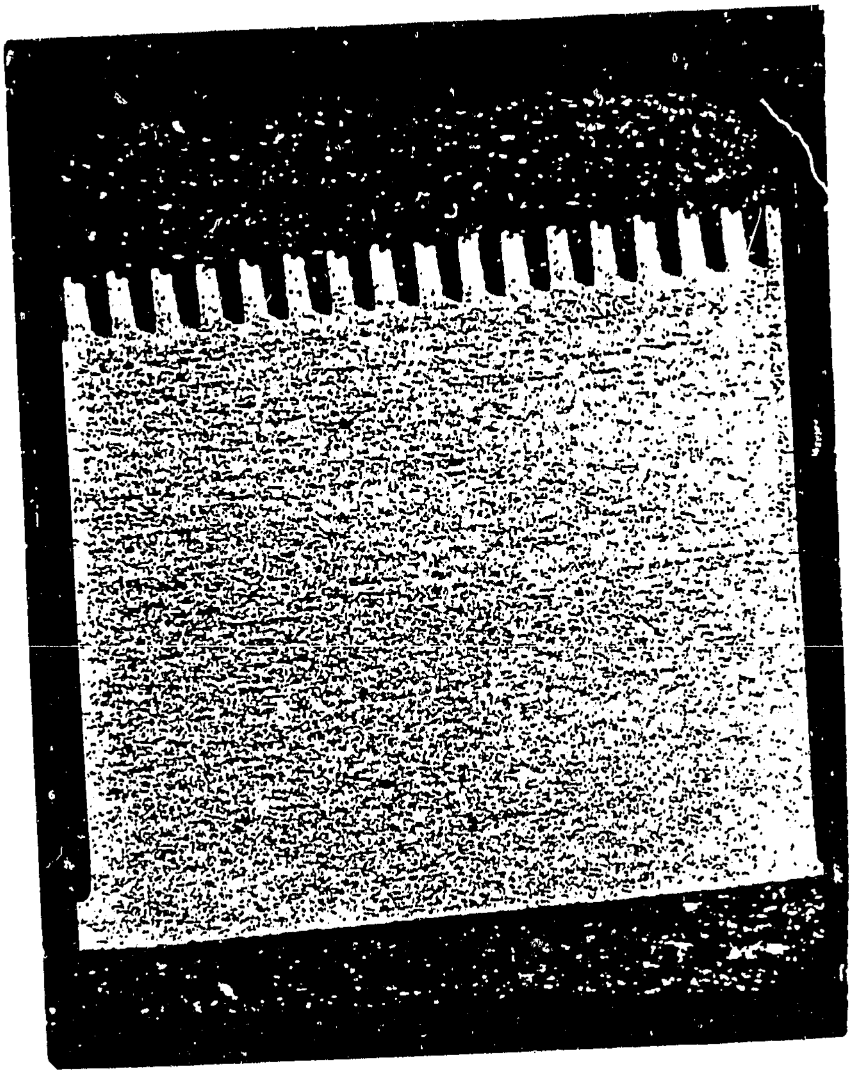
[3] FILL WITH 9 ± 0.5 g OF WATER

[4] INSTALL WITH TEFLON TAPE ON THREADS

SKETCH: JLW 830322-1

J. L. Williams 3-22-83

NOT TO SCALE



MAGNIFICATION: 40X
GROOVE DEPTH 0.00794 in
173 GROOVES PER INCH

FIGURE A-2 PHOTOMICROGRAPH OF CIRCUMFERENTIAL GROOVES

NOTES:

1. FILLET RADII 0.03
2. MATERIAL 6063-T6
3. TOLERANCE PER FED-STD-245 EXCEPT AS SPECIFIED

FULL SIZE

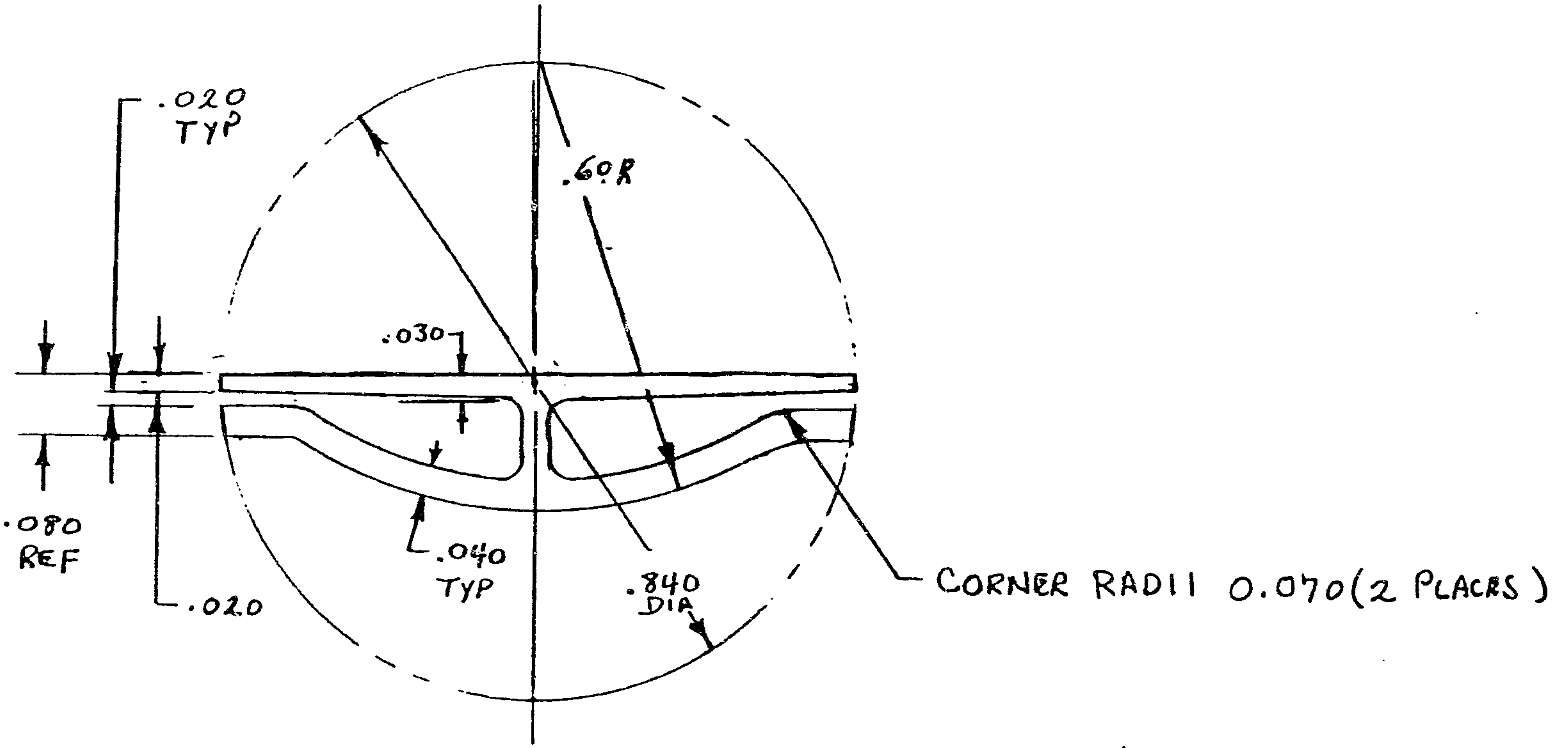


FIGURE A-3 MODIFIED CAT'S EYE ARTERY

CONTR NO.			VOUGHT CORPORATION — Post Office Box 225907, Dallas, Texas 75265
PREPARED	J. OREN	6/21/82	EXTRUSION HEAT PIPE FOUR ARTERY
CHECKED	R. NELSON	6-22-82	
DESIGN GROUP NAME			SIZE / FSCM NO. 80378 / DWG NO. 221-60131 / REV
			SCALE 4X / SHEET 1 OF 1

APPENDIX B
HEAT PIPE CLEAN AND FILL PROCEDURE

WORK ITEMS
HEAT PIPE PREPARATION FOR KC-135 FLIGHT EXPERIMENT

1.0 Make two new flanges (1/2 X 2-1/4 X 2-1/4) identical to the existing plexiglas flange, except material to be Lexan 9034 clear sheet secured from Cadillac Plastic & Chemical Co. on 12-7-82.

2.0 Fabricate and install one fill port at center of the 5.00 long heat pipe opposite heavy internal scratch in accordance with sketch shown in Figure B-1.

3.0 Cut a new artery from new stock (500 ft) of 221-60131 "Heat Pipe Extrusion, Four Artery" received at Vought on or about 11-17-82. Length of artery to be 4.960 ± .005 (record actual length: ________). "Machine" ends of artery smooth and flat for surface seal on Lexan flanges (no adhesive). "Machine" the "width" of artery from existing approx. 0.840 to 0.828 + 0.000, -0.002 in. Record actual machined width ________.

4.0 Proof pressure and leak test the 1.0 "dia. X 5.00" long heat pipe to 80 psig (use old flanges and no artery installed).

5.0 Make-up setup for evacuating and charging heat pipe in accordance with schematic shown in Figure B-2.

6.0 Clean all parts in accordance with the following procedure: (After cleaning, keep as clean as possible and assemble as soon as feasible).

6.1 Clean the Non-Metallic Parts shown in Figure B-2 (includes 2 pcs. Lexan flanges of heat pipe, one piece of Tygon tube, burette) as follows:

Use a warm mild solution of "Alconox" detergent (Alconox Inc. Cat. No. V29706) with no scrubbing, followed by a rinse in deionized water and air dry.

6.2 Clean the 3 pieces of Whitey SS-43F4 Valves shown in Figure B-2 (schematic) as follows:

Flush with TF through open valve. Then submerge valve in TF and open and close valve about 10 times slowly. Then air dry.

6.3 Clean the Aluminum Parts shown on schematic in Figure B-2 (includes the 4.960-in. long artery described in para. 3, the 1" dia. X 5.00-in. long heat pipe, the aluminum tubes and fittings) as follows:

Deliver parts to "The Aluminum Clean Line" (Mr. Jackson, Col. S35 of Bldg. 1, X6259) for cleaning using chemical etch. Clean for purpose of removal of maximum contamination. Artery to be cleaned internally and externally; aluminum tubes cleaned internally (etch will eat up steel sleeves and will remove anodize on aluminum nuts.

7.0 Assemble the heat pipe as follows handling the cleaned parts with clean white gloves:

7.1 Install a Whitey SS-43F4 valve on the heat pipe fill port using Teflon tape on threads. (Shown in schematic on Page 3). Install an 816-4-4D with Teflon tape on valve and cap with AN 929-4 cap asst.

7.2 Install the "4.960"-in. length artery (Par. 3.0) in the heat pipe with the flat surface perpendicular to the fill port.

7.3 Install two O-rings (size 2-020, compound 70 silicone) (cleaned per par. 6.1) in the Lexan flange grooves.

7.4 Assemble Lexan flanges on heat pipe using 4 pcs. of 3/16-in. machine bolts and nuts - - tighten nuts in turn and in steps until the distance between flanges, measured at 4 places 90° apart, is same as length of artery measured and recorded in para. 3.0 , +0.000, -0.005

(Valve recorded in para. 3.0 page 1 = ____________)

(Final length between flanges at 4 places 90° apart =

7.5 Weigh the heat pipe (capped as specified in para. 7.1 above). Record the weight: __________gms. (This is the heat pipe tare (empty) weight).

8.0 Assemble the setup for evacuating and charging the heat pipe and install the heat pipe as shown in the schematic shown on Figure B-2.

9.0 Evacuate the heat pipe by operating the vacuum pump with valve V-3 closed, V-1 and V-2 open, and energizing the heat pipe heater to get a temperature of 200 $\pm 0_5$ Deg.F. on the 1" dia. heat pipe. Hold conditions of 200 $\pm$ 0_5 Deg.F. and an indicated vacuum pressure of 1.0 X 10^{-6} torr or less for a minimum of 24 hours.

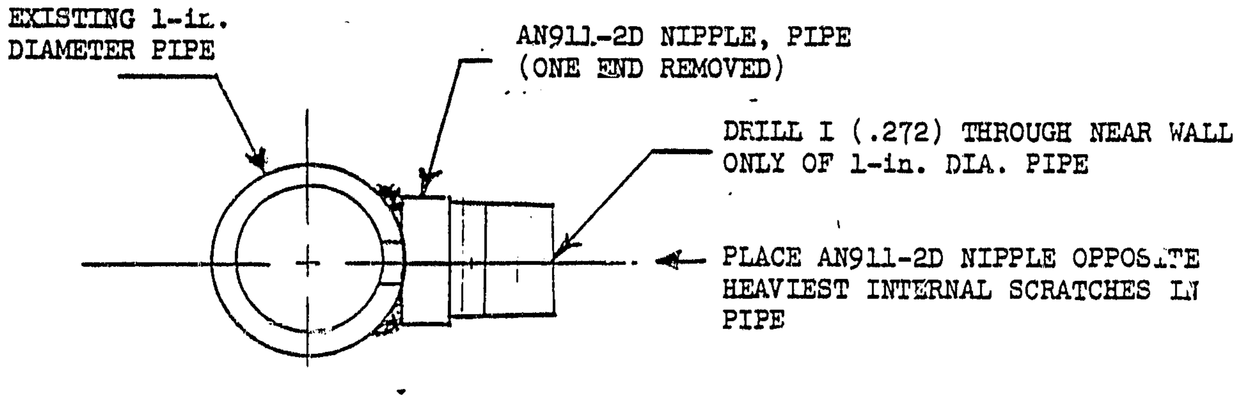
10.0 After completion of evacuation of the heat pipe (par. 9.0 above), charge heat pipe by closing valve V-2 and cracking valve V-3 extremely slowly until 9.0 $\pm$ 0.5 cc of H_2O enter system from the burette, at which time valve V-3 is to be closed.

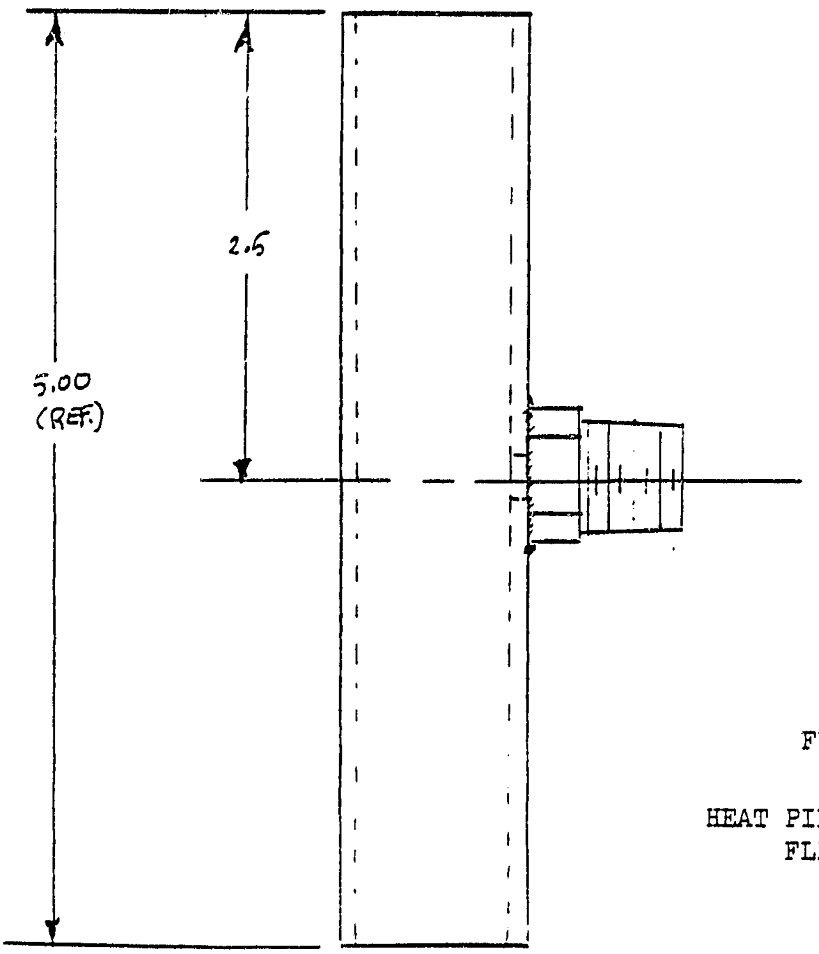
11.0 Remove the connection between valve V-3 and the burette. Remove the connection between valve V-2 and the vacuum pump. Manually move the heat pipe and the setup remaining connected to it to permit gravity drainage of all liquid water into the heat pipe. Then disconnect the 1/4-in. aluminum tubing from valve V-1 after closing valve V-1. Use the cleaned AN 929-4 cap to cap the valve V-1 open port.

12.0 Weigh the charged heat pipe (capped as specified in par 11.0 above). Record the gross wt. =____________gms. Subtract the heat pipe tare (empty) weight which was measured and recorded in par 7.5 and record the weight of charged water = ____________gms.

FIGURE B-1

WORK ITEMS
HEAT PIPE PREPARATION FOR KC-135 FLIGHT EXPERIMENT





NOTE: 1. A Whitey SS 43F4 valve will be mounted directly to the AN911-2D nipple, with TEF-ON tape on threads.

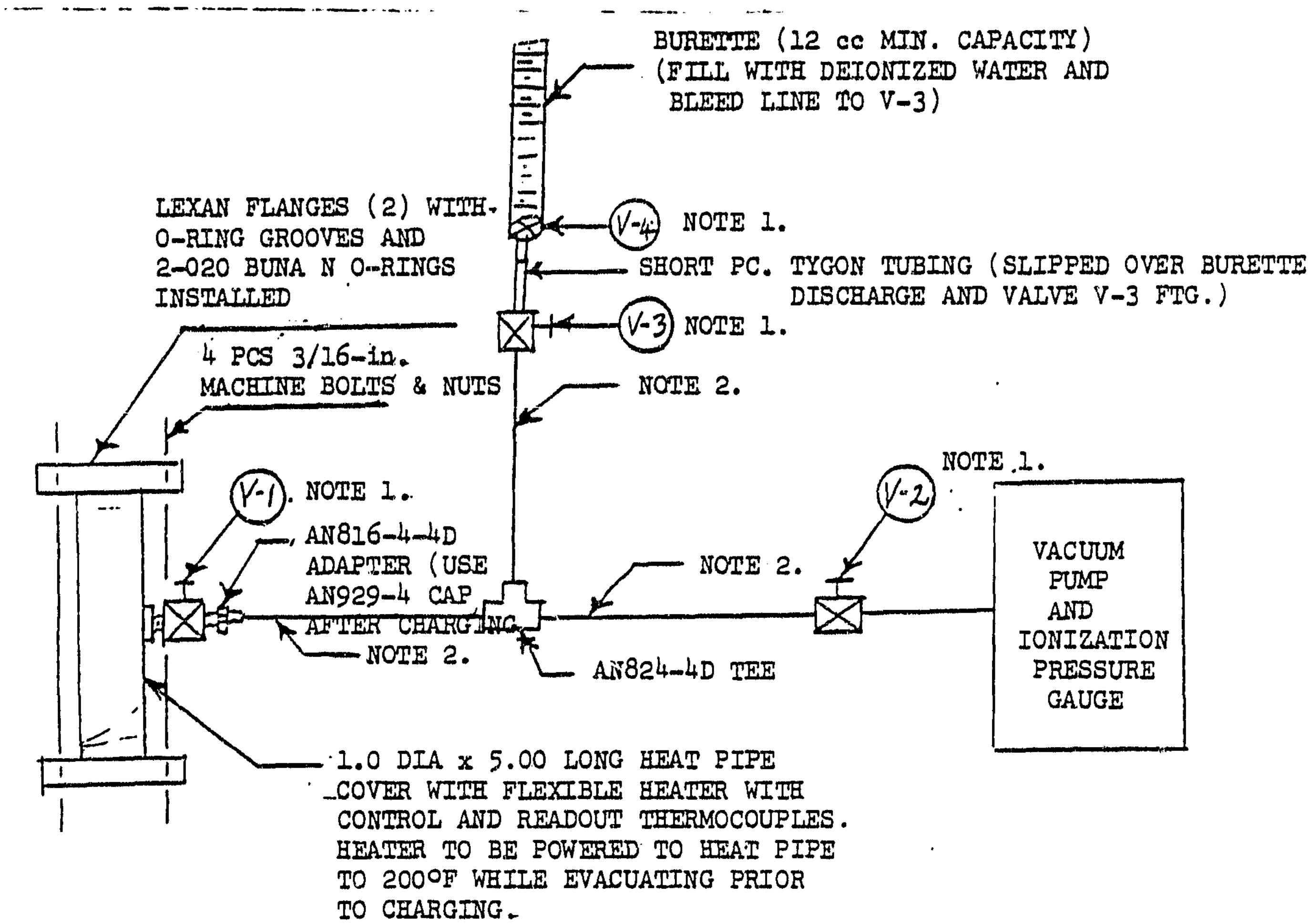
FILL PORT DETAIL

HEAT PIPE PREPARATION FOR KC-135
FLIGHT EXPERIMENT

FIGURE B-2

WORK ITEMS
HEAT PIPE PREPARATION FOR KC-135 FLIGHT EXPERIMENT

HEAT PIPE SETUP SCHEMATIC
FOR
EVACUATING AND CHARGING HEAT PIPE



NOTES:

1. V-1, V-2 and V-3 are Whitey SS-43F4 ball valves. V-4 is a glass stopcock on the burette.
2. These 3 places are to be 1/4 in. DIA aluminum tubes, as short as feasible with flared ends, nuts, and sleeves.
3. All parts to be cleaned per para. 6, page 1 of the Work Item List.
4. This setup to be used to charge the heat pipe with 8.5 gms of deionized water.